The CERES calibration strategy of the geostationary visible channels for CERES cloud and flux products

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ABSTRACT

The Clouds and Earth's Radiant Energy System (CERES) project has greatly improved the understanding of the role of clouds and energy cycles in global climate studies. CERES flux and cloud properties rely on not only CERES broadband fluxes and MODIS cloud properties but also on operational geostationary (GOES, METEOSAT, MTSAT) derived fluxes and clouds, which are acquired between CERES measurements such to properly account for the diurnal cycle. The high quality of the CERES products is dependent on a consistent radiometric calibration of the un-calibrated geostationary visible sensors and MODIS. To achieve this consistency, the calibration of a reference sensor must be transferred to the other instruments. Historically, Terra-MODIS and Aqua-MODIS, both of which employ solar diffusers, have been regarded as having a well-calibrated visible channel (650 nm). Recent analysis has revealed the Aqua-MODIS instrument to be more stable than the MODIS instrument onboard the Terra satellite. For this reason, Aqua-MODIS has been chosen as the reference sensor whereas Terra-MODIS adjustments can be used to put the instrument on the same radiometric scale as Aqua-MODIS. The ray-matching technique is used to transfer the calibration of the well-calibrated MODIS instrument to the un-calibrated GEO sensors. Additionally, empirically derived models for pseudo-invariant test sites and deep convective clouds (DCC) have been developed and applied for monitoring and validating the GEO calibration.

Multiple pseudo-invariant test site and DCC absolute calibration methodologies are compared. Latest results show that GOES-13 response has drifted 5-6 percent in its first 15 months of operation. The Aqua/Terra-MODIS cross-calibration trends are in agreement with calibration trends obtained from pseudo-invariant test sites and DCC. These results are in preparation for CERES Edition4 products, which will include updated geostationary calibration coefficients and cloud retrieval improvements.

Keywords: CERES, Radiometric Calibration, Geostationary, Deep Convective Clouds (DCC), Pseudo-Invariant Test Sites, Aqua-MODIS, GOES-13

1. INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES) project supplies valuable data products to the science research community. Among these data products are various surface and TOA products that include solar-reflected and Earth-emitted radiation data. Some of these products rely on not only CERES measurements, but also on the measurements of other Earth Observing System (EOS) instruments. For example, the CERES cloud products rely on the MODerate resolution Imaging Spectroradiometer (MODIS) instrument whereas the CERES TOA broadband flux record incorporates 3-hourly geostationary (GEO) fluxes to derive broadband fluxes between CERES measurements onboard the sun-synchronous Terra (10:30 AM) and Aqua (1:30 PM) orbits. Adding the GEO measurements enables a more accurate portrayal of the diurnal cycle that cannot be achieved when utilizing only the two daily CERES measurements. To successfully merge the CERES and GEO fluxes into one product, however, they must first be placed on a consistent radiometric scale.

Although the CERES instrument's calibration and stability is closely monitored and maintained via a quality on-board calibration system, GEO visible channels must be vicariously calibrated due to a lack of on-board calibration.

Until recently, the CERES project has had its GEO calibration based on an inter-calibration technique whereby ray-matched MODIS and GEO data are collected and monitored over time. The stability of this method was validated through the use of several pseudo-invariant desert sites as well as deep convective cloud (DCC) trending. Use of this inter-calibration method with MODIS relies on the accurate and stable calibration of the MODIS instrument. Recent analysis of MODIS on the Terra and Aqua spacecrafts have shown Aqua-MODIS to be the better characterized and more stable instrument; therefore, the CERES GEO calibration team has chosen to make this the reference sensor for the GEO calibration. Reliance on one method, let alone one instrument, for calibration is a risky decision, however. Therefore, the latest approach by the CERES team is to develop alternative absolute calibration approaches capable of linking the radiometric calibration of past, present and future sensors.

This paper concentrates on the recent progress of these newly developed independent absolute calibration methods. First, methodologies for ray-matching will be reviewed, followed by descriptions of the pseudo-invariant desert and DCC absolute calibration techniques. The application of the various methodologies will then be demonstrated for the GOES-13 GEO sensor, and conclusions will be presented.

2. REFERENCE SENSOR SELECTION

The lack of on-board visible channel calibration on GEO satellites makes vicarious calibration of these sensors prior to their use in CERES data products imperative. Unfortunately, a direct calibration transfer from the CERES instrument is not an option because of the broadband design of the CERES spectral response functions (SRFs) compared to the narrowband SRFs operational on GEO sensors. Therefore, an alternative reference sensor, MODIS in this case, must be used for calibration transfer. MODIS is widely regarded as having a consistent, accurate band 1 (0.65 μm) radiometric response, which fortunately aligns quite well with many GEO SRFs. Recent analysis, performed in a joint effort between the MODIS calibration team and NASA Langley GEO calibration team (in preparation for publication), has shown that Aqua-MODIS is rather stable (within 0.5% over the 9+ year lifetime) as compared to Terra-MODIS (approximately 2% degradation over the 11+ year lifetime), and consequently should be used as the reference sensor for inter-calibrations. Time dependent correction factors were developed within the NASA Langley GEO calibration group in order to make it possible to put Terra-MODIS on the same radiometric scale as Aqua-MODIS, thereby giving two independent sources of calibration to be used with the ray-matching inter-calibration technique (in preparation for publication).

3. RAY-MATCHING-BASED ABSOLUTE CALIBRATION

Ray-matching inter-calibration is a technique in which the calibration from a well-calibrated sensor is transferred to an un-calibrated sensor using co-incident, co-angled, and co-located regions imaged by both the sensors[1]. For this study, the GEO raw counts, which are proportional to radiance, and MODIS L-1B spectral radiance data are binned into 0.5° latitude by 0.5° longitude regions within a calibration domain that is typically ±20°E,W and ±15°N,S of the GEO sub-satellite point whenever there is a co-incident, co-located match. First, a variety of filters are applied to eliminate regions likely to increase uncertainty in the inter-calibration, and then the regions are corrected for spectral band differences, regressed, and monitored over time.

A spatial standard deviation filter is applied to remove regions with low homogeneity. This filter's threshold is empirically determined for each sensor, but typically removes regions with spatial standard deviations greater than 3-8 percent of the mean. Any region with a land area percentage greater than 10% is removed from consideration due to the high seasonal variability of the relative spectral response over land within the tropical domain. Also, any regions over water in near-sun-glint conditions were eliminated. The solar zenith angle (SZA), view zenith angle (VZA), and azimuth angle (AZA) of the remaining regions from both sensors are then matched within 5°, 10°, and 15° respectively. This remaining dataset is now corrected for spectral differences in the GEO and MODIS SRFs using the SCIAMACHY spectra data.

The spectral correction performed in this study follows closely the technique described by Doelling et al.[2], where the spectra from each appropriate SCIAMACHY pixel (over all-sky ocean, in the calibration domain of GOES-

13) was convolved with both the GOES-13 and Aqua-MODIS SRFs to compute pseudo-imager radiances. A second-order fit to the pseudo-imager radiances is the radiance-dependent spectral band adjustment factor (SBAF) that should be applied to MODIS radiances in order to arrive at a predicted GOES-13 radiance. Figure 1a includes the average all-sky ocean spectra over the GOES-13 calibration domain as well as the SRFs for GOES-13 and Aqua-MODIS. Figure 1b gives the pseudo-imager radiances of over 60000 SCIAMACHY footprints and the associated second order SBAF correction for this sensor pair over all-sky ocean. The second order correction factor satisfactorily fits the pseudo-imager radiances throughout the dynamic range and shows a relatively small correction (~4 percent at 400 $Wm^{-2}sr^{-1}\mu m^{-1}$).

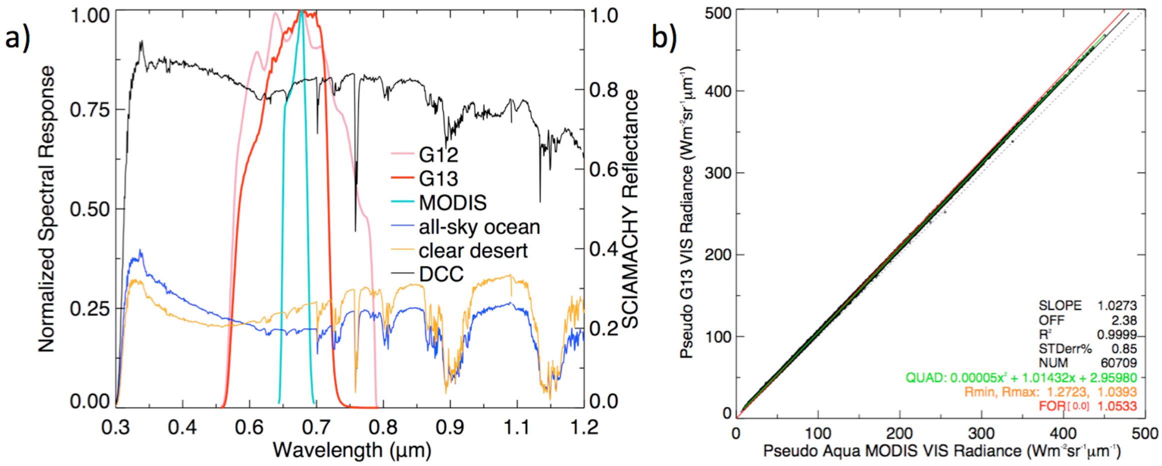

Figure 1: a) SCIAMACHY reflectance spectra for all-sky ocean, clear Sonoran desert, and DCC along with SRFs for GOES-12 (G12), GOES-13 (G13), and Aqua-MODIS. b) Pseudo-imager radiance for GOES-13 and Aqua-MODIS over clear-sky ocean within the GOES-13 calibration domain.

After applying the appropriate corrections, the GOES-13 raw counts are regressed against the SBAF corrected Aqua-MODIS radiances on a monthly basis. This regression is forced through the space count of GOES-13 (29.0) and the slope of the forced regression represents the absolute gain of the GOES-13 sensor. This gain can be used to convert the raw count of the GOES-13 pixel into a physical quantity (L_λ, spectral radiance) via

$$L_\lambda = \text{Gain} \times (\text{DN} - \text{SpaceCount}). \tag{1}$$

This procedure is repeated each month and the absolute gains are trended over time to monitor the instrument response of GOES-13. Figure 2a and 2b depict typical monthly scatterplots, with the forced regression, for GOES-13 versus Aqua-MODIS and GOES-13 versus Terra-MODIS (with corrections), respectively. The Terra-MODIS corrections were derived from Terra and Aqua simultaneous nadir overpass (SNO) measurements, allowing the radiometric scaling of Terra to Aqua. Figure 2c shows the GOES-13 absolute gain trends derived via the two MODIS sensors where coefficients a_0, a_1, and a_2 are used to find gain via

$$\text{Gain} = a_0 + (a_1 \times \text{DSL}) + (a_2 \times \text{DSL}^2). \tag{2}$$

The GOES-13 absolute calibration, based on Terra and Aqua-MODIS inter-calibration, is within 0.8% over 15 months. GOES-13 has degraded by 4.5% and 4.3% per year, based on Terra and Aqua, respectively. The inter-calibration of Aqua to Terra and then from Terra to GOES-13 is very consistent with the inter-calibration of Aqua directly to GOES-13, validating the robustness of the ray-matching technique. The ray-matching technique is more successful over bright cloud domains, since it increases the dynamic range of the radiance pairs, used to derive the regression. The standard error of the Terra/GOES-13 regression in Figure 2b is much lower than the corresponding Aqua/GOES-13 due to the greater dynamic range of the matched pixel radiances.

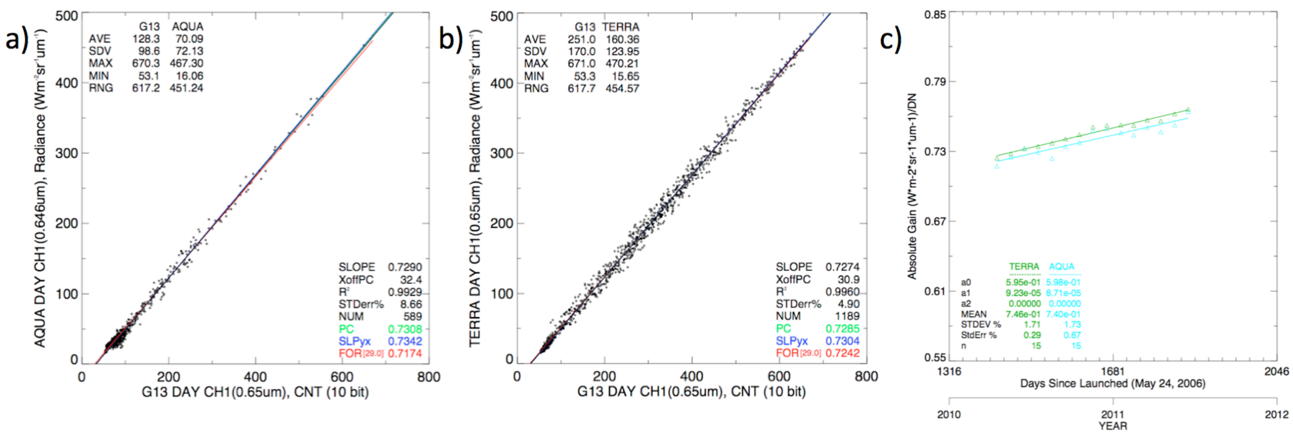

Figure 2: a) Ray-match results for Aqua-MODIS to GOES-13 inter-calibration during month of April 2010. b) Ray-match results for Terra-MODIS (with corrections) to GOES-13 inter-calibration during month of April 2010. c) Timeline of absolute gains derived via ray-matching for both Aqua and Terra-MODIS to GOES-13 inter-calibration.

4. DESERT-BASED ABSOLUTE CALIBRATION

Pseudo-invariant calibration sites on the Earth's surface have become increasingly used over the past decade for long-term radiometric trending of visible satellite sensors. The underlying assumption for this technique is that the reflectance of these ground targets remains constant over time, and any change observed in satellite instrument response to these targets over time would be caused by the degradation of the instrument itself. This section describes desert-based techniques for long-term radiometric stability monitoring and calibration of GOES visible sensors using the Sonoran desert site. A recent study has shown that certain regions of this site are fairly stable over time[3,4,5]. This paper uses a 0.2°x 0.2° region of interest (ROI) centered at 32.10° latitudes and -114.50° longitudes, and demonstrates the proof of concept as applied to the GOES-12 and -13 visible channels.

The GOES-12 and -13 visible pixel raw counts acquired over the ROI were averaged after subtracting the space count (29.0). On a clear-sky day, the pixels are homogeneous and the spatial standard deviation is low. Any increase to the standard deviation can be attributed to the presence of a cloud in the scene. Based on the visible inspection of the standard deviation profile on clear-sky days, a threshold was determined to identify and eliminate the cloudy scenes (Figure 3a). The filtered and averaged pixel data were then used in monitoring the stability of both GOES visible sensors as well as in their inter-calibration.

4.1 Stability monitoring using de-seasonalization of desert mean raw count

The clear-sky daily mean raw counts are averaged on a monthly basis for consistency with the ray-matching technique. Figure 3b shows the GOES-12 monthly means plotted against days since launch (DSL). The seasonal cycles displayed in Figure 2 can be attributed to the variation of solar geometry throughout a year[6]. In order to reveal the true instrument response, the monthly mean raw counts must be appropriately de-seasonalized. To achieve this, first a 12-month running mean is computed. Second, a relative ratio between the month and the running mean is determined. Third, an average relative ratio for each of the 12 months is computed, and this climatology ratio is then applied to de-seasonalize all the monthly raw counts for the time period. The de-seasonalized means are then plotted against DSL to get the relative stability of the GOES-12 visible channel over its lifetime (Figure 3c).

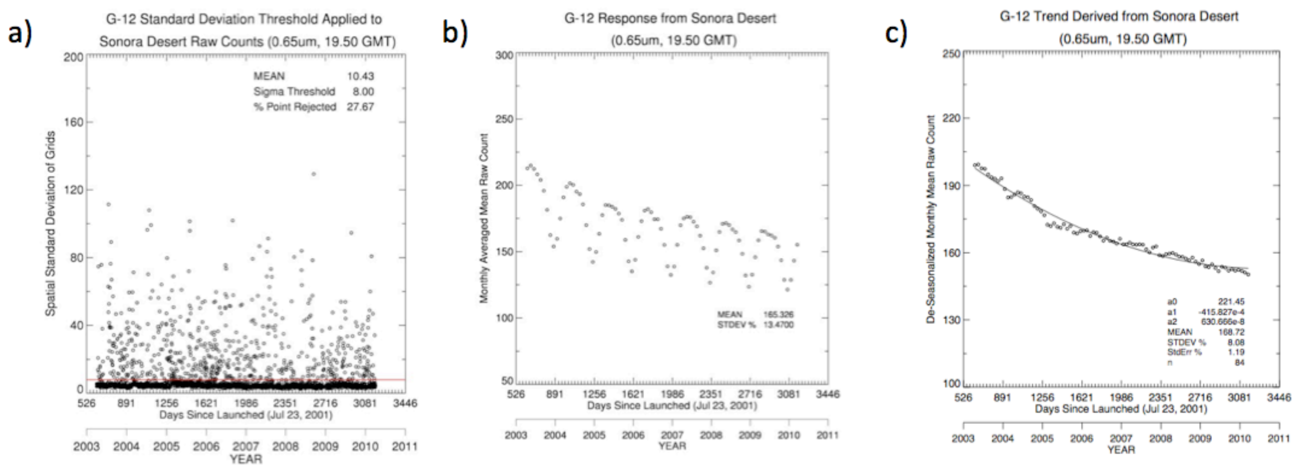

Figure 3: a) Sonoran desert standard deviation cloud masking results for GOES-12. b) GOES-12 monthly averaged mean raw counts versus DSL for Sonoran desert showing strong seasonal effects. c) GOES-12 monthly averaged deseasonalized mean raw counts for Sonoran desert showing the degradation trend of GOES-12.

4.2 Seasonal desert model approach

The seasonal cycles in the GOES-12 monthly mean plot (Figure 4a) would be consistent throughout the lifetime if the instrument were stable, as the site itself is not changing. This suggests a potential for constructing a seasonal model for predicting the TOA radiance for any day of year, as the view zenith angle for GOES-12 at sub-satellite position never changes, and the solar cycles repeats every year. However, in order to derive such a model, consistently calibrated GOES-12 TOA radiances over the lifetime are required. Figure 4a shows the GOES-12 calibrated TOA radiances, based on GOES-12 and Aqua-MODIS ray-matched inter-calibration, coming from the ROI over the Sonoran desert site at approximately local noon. The similar day radiances can be averaged to derive the daily seasonal model (Figure 4b). This seasonal model can be used to predict the at-sensor pseudo-radiance observed by GOES-12 or any other similar instrument at the same location under identical viewing and solar illumination conditions.

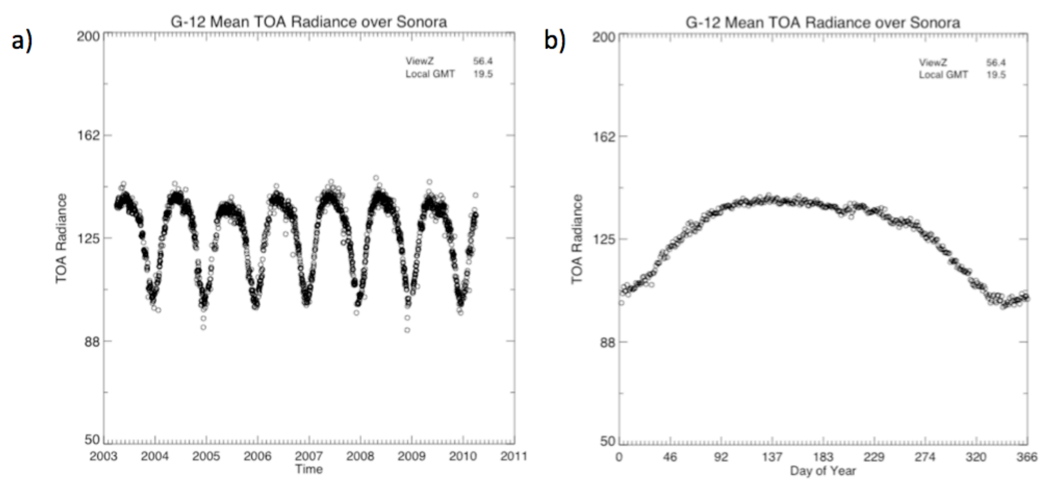

Figure 4: a) GOES-12 mean TOA radiance at the Sonoran desert, derived by applying ray-matched gains from Aqua-MODIS to monthly averaged mean raw counts. b) Sonoran desert climatology where each day of the year is represented by the average TOA radiance from that day throughout the lifetime of GOES-12.

4.3 Desert bidirectional reflectance distribution function (BRDF) approach

This method uses a site-specific BRDF model that was developed based on GOES-12 observations. When considering geostationary satellites, the BRDF model is a function of illumination and relative azimuth between the satellite and the sun, as the view angle is always constant. For the Sonoran desert site, a linear combination of two kernel-driven functions[7] is used to derive the BRDF equation, expressed as:

$$\rho(\theta_s, \theta_v, \phi) = k_0 + k_1 f_1(\theta_s, \theta_v, \phi) + k_2 f_2(\theta_s, \theta_v, \phi), \quad (3)$$

where $\rho(\theta_s, \theta_v, \phi)$ is the bidirectional reflectance of the surface in a particular direction, θ_s, θ_v, and ϕ are solar zenith, view zenith, and relative azimuth angles, f_1 and f_2 are analytical functions determined explicitly for each combination of θ_s, θ_v, and ϕ values of the solar and viewing geometric angles, and k_0, k_1, and k_2 are the surface parameters related to the physical structure of the reflecting surface and are derived empirically using seven years of calibrated GOES-12 data over the Sonoran desert site. Once the model parameters are computed, the bidirectional reflectance factors for GOES-12, or similar instruments at the same sub-satellite point, can be estimated from the model by knowing the solar and viewing geometric angles. Once the at-sensor reflectance is estimated from the model, the gain of the sensor can be derived from the observed mean raw count.

4.4 Desert calibration results comparison

These three techniques are first tested with GOES-12 to check their consistency with the ray-matching technique. Figure 5 shows the absolute gains of GOES-12 as a function of DSL derived from the seasonal and BRDF approaches with the relative trend derived from the deseasonalization of monthly mean raw count.

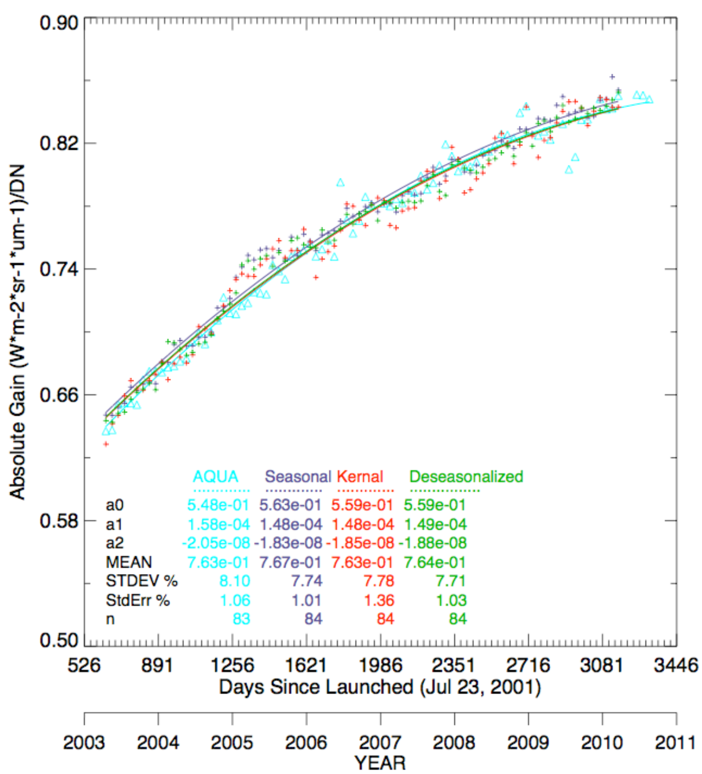

Figure 5: Comparison of Aqua-MODIS ray-match results and desert based calibration methods. The seasonal model and kernel driven model are both absolute calibration techniques whereas the deseasonalization method is simply a trending method that is scaled, for comparison, to the midpoint of the Aqua-MODIS ray-match curve.

The three data sets and corresponding fits are rather consistent with the second order fit from the ray-matching method for GOES-12 and Aqua-MODIS. This suggests the desert calibration methodology is limited by the stability of the earth target rather than the approach. This is evident in the year 2005 when there was significant precipitation on the Sonoran desert darkening the ROI[3] and possibly after 2009. The desert was most stable during 2003 and 2004. The absolute GOES-13 gain derived from the seasonal or BDRF kernel desert approach is within 0.5% with very similar stability over time, indicating both approaches are comparable. The seasonal approach was selected as the primary CERES desert technique simply by the fact it has the smaller standard error.

5. DEEP-CONVECTIVE-CLOUD-BASED ABSOLUTE CALIBRATION

The use of DCC for trending purposes was first developed by Hu et al. to examine the relative stability of CERES on TRMM and Terra as well as VIRS and Terra-MODIS imagers[8]. Their analysis, based upon the assumption that DCC broadband albedo response is constant over time, uses narrowband to broadband conversions to verify the stability of the two imagers over 8 months spanning 2000 to 2002. Later, Doelling et al. refined the DCC technique, using DCC to estimate calibration trends of AVHRR radiance data without the conversion from narrowband to broadband[9]. Later, Minnis et al. used DCC to validate the onboard calibration of VIRS and Terra-MODIS[10]. Doelling et al. also characterized DCC narrowband albedo response by analyzing SZA, VZA, AZA, Band 31 (11 μm) brightness temperature ($BT_{11\mu m}$), and geo-location effects on Aqua-MODIS DCC response[11]. The conclusions of that research support that DCC response can be affected by both $BT_{11\mu m}$ and geo-location. The purpose of this study is to expand on the DCC calibration methods used in the past, and extend the technique for use as an absolute calibration source.

The previous research on DCC trending was based on the assumption that DCC response is constant throughout time. Using this assumption, if an expected radiance model can be assigned to the DCC response, DCC could be used as an absolute calibration source much in the same way pseudo-invariant deserts can be used as an absolute calibration source. Aqua-MODIS is known to be well-calibrated and views DCC on a consistent basis. Therefore, assigning an expected radiance model to DCC can be accomplished via Aqua-MODIS. The technique presented by Doelling et al. (2004) was used to trend Aqua-MODIS DCC pixels throughout time. In summary, probability density functions (PDFs) of normalized visible DCC radiance pixels (VIS) between 30°N and 30°S were compiled each month. A DCC radiance pixel was valid provided it met the following criteria: $BT_{11\mu m}$ < 205.0° K, SZA < 40°, VZA < 40°, 10° < AZA < 170°, $\sigma(BT_{11\mu m})$ < 1.0° K, and σ(VIS) <3%. The anisotropy of each DCC pixel was removed by multiplying by the appropriate CERES bidirectional reflectance distribution function model value[12]. Next, the pixel was normalized to a common set of angles using the CERES SZA-dependent albedo model for ice clouds with an optical depth of 50. The normalized DCC radiances were then compiled into PDFs for each month, and the modes and means of the PDFs were tracked throughout time to monitor the expected DCC response. In order to account for and reduce possible geo-location effects, the same procedure was completed using only pixels within the GOES-13 calibration domain: 250° to 305° longitude. Figure 6a displays the global domain PDF for July 2003, whereas Figure 6b shows the global domain PDFs for every sixth months throughout the lifetime of Aqua-MODIS. Figure 6c compares the mean and mode responses over the lifetime of Aqua-MODIS for the global domain and the GOES-13 domain.

Doelling et al. suggested that the DCC nadir radiance could vary by 5% geographically using the mean response[11]. This implies that in order to transfer the Aqua-MODIS calibration to GOES-13, only the GOES-13 domain should be considered to compute the DCC nadir radiance. In Figure 5c, the red circles (GOES-13 domain mode response) and black circles (global domain mode response) have average responses within 0.3 percent, whereas the red x's (GOES-13 domain mean response) and black x's (global domain mean response) average responses differ by 2.3 percent. This signifies that tracking the mode response is the more robust method and is less dependent on geo-location. The GOES-13 domain mode response degrades by less than 1 percent over the lifetime of Aqua-MODIS, confirming that Aqua-MODIS has a stable, well-calibrated 0.65-μm sensor. This analysis has revealed the expected normalized Aqua-MODIS DCC mode response to be 719.1 $Wm^{-2}sr^{-1}\mu m^{-1}$ over the GOES-13 domain.

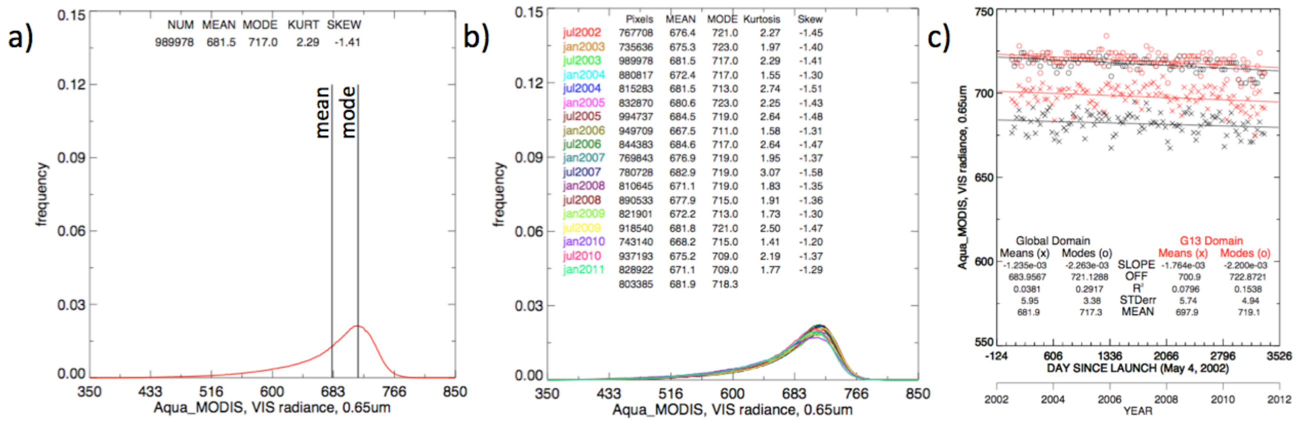

Figure 6: a) DCC PDF from July 2002 showing the mean and mode response for Aqua-MODIS global domain. b) DCC PDFs for every six months throughout the lifetime of Aqua-MODIS showing that the mode and mean response for the global domain throughout time is stable. c) Lifetime mode and mean DCC trends comparing DCC results from the global domain to results from the GOES-13 domain.

In order to transfer calibration to the GOES-13 sensor, spectral differences must be taken into account. A SCIAMACHY correction was determined using a similar procedure to that described in the ray-matching section. Instead of convolving all-sky ocean SCIAMACHY spectra with the Aqua-MODIS and GOES-13 SRFs, spectra identified as DCC were convolved. The factor to convert the Aqua-MODIS expected DCC response to the GOES-13 expected DCC response, calculated as the average ratio of resulting pseudo-imager radiances, was found to be 1.041. After applying the spectral correction, the expected normalized GOES-13 DCC mode response was found to be 748.3 $W*m^{-2}*sr^{-1}*\mu m^{-1}$.

In order to transfer the Aqua-MODIS calibration to GOES-13, the GOES-13 DCC nadir radiance is assumed to be equivalent to Aqua-MODIS, except for SRF differences. Now that an expected radiance for GOES-13 DCC response has been established, the raw GOES-13 DCC data must be normalized to the same viewing/solar geometry as was used for tracking Aqua-MODIS DCC response. An identical procedure to the one described for Aqua-MODIS was followed. The same CERES anisotropy and albedo models that were used for modeling Aqua-MODIS DCC response were applied to all DCC raw VIS counts found within the GOES-13 calibration domain for images acquired within approximately one hour of local noon. The images taken about noon give the greatest signal to noise ratio of the GOES-13 detector. These raw counts had the known space count of 29.0 subtracted prior to the normalization, thereby making the raw counts directly proportional to radiance. Figure 7a shows the normalized GOES-13 raw-count PDFs over the GOES-13 operational lifetime, while Figure 7b shows the lifetime trends of the mode and mean response.

From Figure 7a and 7b, it is clear that the response from GOES-13 is not stable like the Aqua-MODIS DCC response. This instability owes itself to a decrease in sensor response for GOES-13. To obtain an absolute calibration for this sensor, the absolute gain ($Wm^{-2}sr^{-1}\mu m^{-1}$/DN) can be found directly for each month by dividing the expected GOES-13 DCC radiance (748.3 $Wm^{-2}sr^{-1}\mu m^{-1}$) by the normalized mode DCC count for that month. Figure 8 shows the result: a timeline of absolute gains that can be used to convert a GOES-13 count into spectral radiance using (Eq. 1).

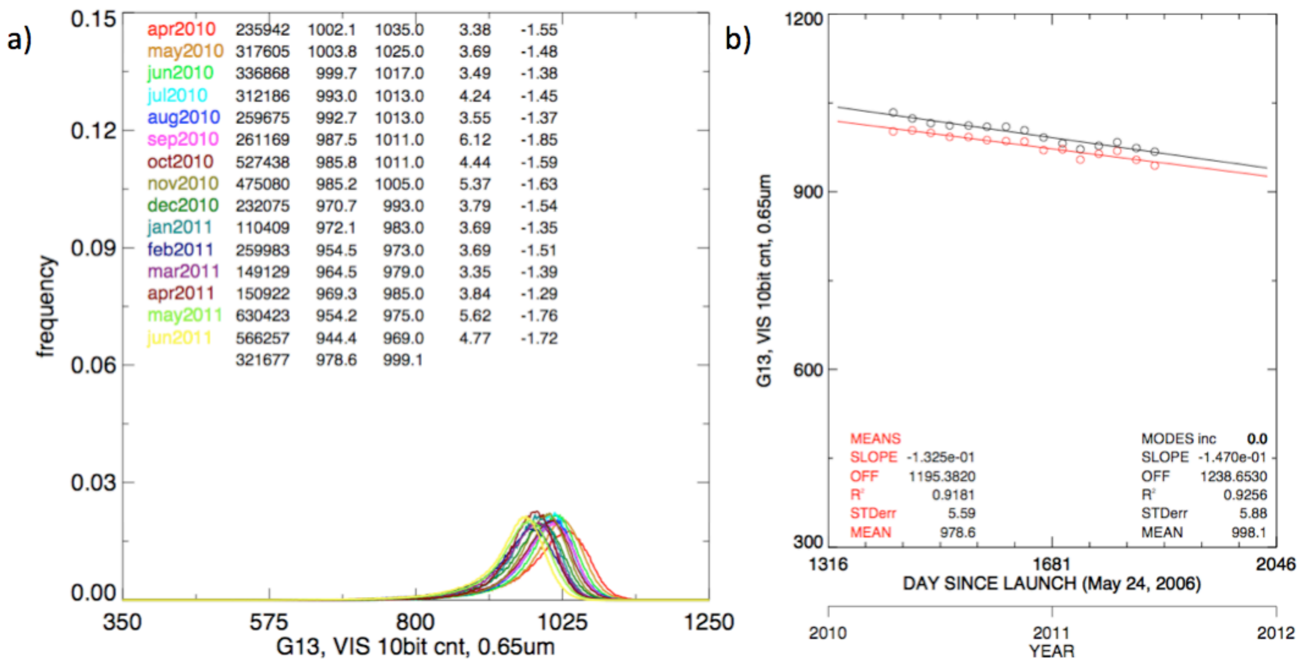

Figure 7: a) DCC PDFs throughout the lifetime of GOES-13 showing degradation of the raw counts. b) GOES-13 DCC mode and mean trends show a linear degradation of the raw counts observed for DCC at local noon in the GOES-13 domain.

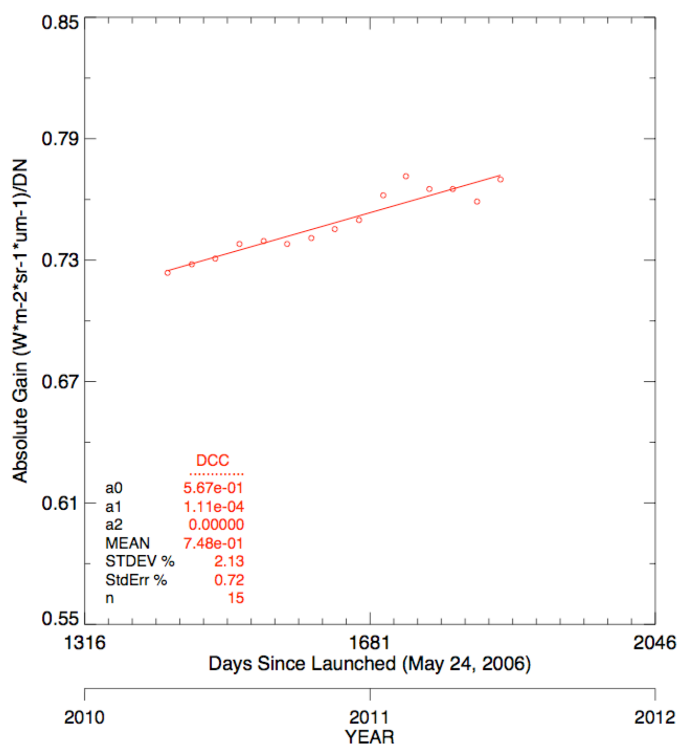

Figure 8: Absolute calibration transfer for GOES-13 using DCC modes gathered within theGOES-13 domain at local noon.

Doelling et al. indicated a slight dependency of DCC nadir radiance with the IR temperature threshold[11]. To ensure an accurate calibration transfer of the reference sensor using DCC, the $BT_{11\mu m}$ effects should be quantified and minimized. This would imply that GOES-13 should use the same $BT_{11\mu m}$ threshold as Aqua-MODIS to guarantee that the $BT_{11\mu m}$ are similar and can be easily compared. In Figure 9a and 9b, a ray-match of GOES-13 and Aqua-MODIS $BT_{11\mu m}$ shows that a daytime bias (GOES – MODIS) of approximately 1.5° K exists at 205° K.

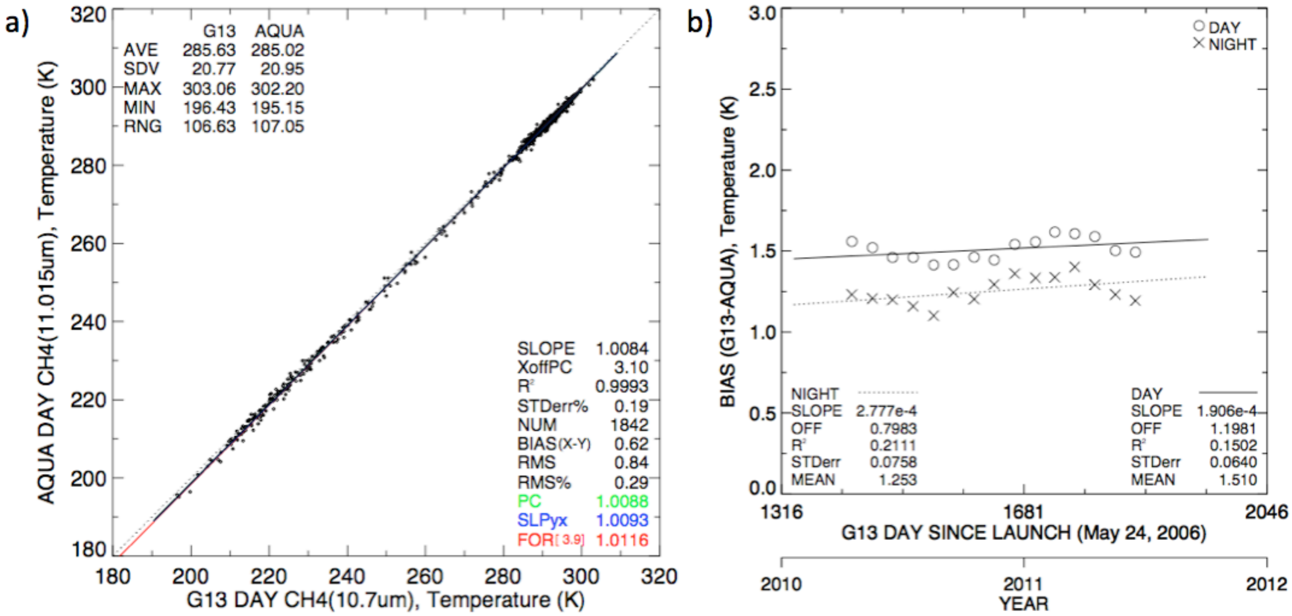

Figure 9: a) Ray-match results for Aqua-MODIS to GOES-13 inter-calibration of the $BT_{11\mu m}$ during April 2010 show a potential bias between the GOES-13 and the Aqua-MODIS brightness temperatures. b) Lifetime trend of the GOES-13 minus Aqua-MODIS $BT_{11\mu m}$ bias at 205° K showing a 1.5° K bias during the daytime ray-matches.

Assuming Aqua-MODIS as truth, applying a 1.5° K temperature correction to the GOES-13 data before identification of DCC pixels would ensure a valid comparison of the typical DCC identified by Aqua-MODIS to the DCC identified by GOES-13. To minimize the DCC diurnal effects, the GOES-13 data centered on 1:30 PM local time can be used instead of local noon. This adjustment ensures matching image acquisition times with the sun-synchronous Aqua orbit that always has daytime equator crossing times of 1:30PM local time. Table 1 compares the absolute gains obtained using GOES-13 data with and without $BT_{11\mu m}$ and diurnal adjustments.

	Noon	**Noon BT_{11} Adj.**	**1:30PM**	**1:30PM BT_{11} Adj.**
Modes	0.7500	0.7513	0.7484	0.7492
Means	0.7423	0.7458	0.7417	0.7453

Table 1: GOES-13 DCC absolute calibration averages showing negligible effects brought on by diurnal and $BT_{11\mu m}$ effects.

As shown in Table 1, neither the GOES-13 $BT_{11\mu m}$ adjustments nor the diurnal adjustments created a significant change in the GOES-13 DCC average gains. For the mode method, the difference between gains derived at noon and the gains derived at 1:30 PM with the $BT_{11\mu m}$ adjustment was less than 0.2 percent. The mean method had a slightly larger difference than the mode method but was still within 0.5 percent. These results are a positive reflection on the DCC calibration transfer algorithm, signifying a strong, thorough methodology.

6. AQUA-MODIS TO GOES-13 INTER-CALIBRATION SUMMARY

To summarize and compare the techniques described in this paper, four independent calibrations (Aqua-MODIS ray-matching, Terra-MODIS ray-matching, DCC, and desert) were transferred to GOES-13. The ray-matching technique follows the methodology described previously. The Terra-MODIS calibration was first adjusted to Aqua-MODIS using SNO measurements before applying the ray-matching technique. For desert calibration, the GOES-12 seasonal model was used to calibrate GOES-13 data. This approach uses the local noontime data over the Sonora Desert from both instruments. Given that their view angles to the target are the same, the calibration can be easily transferred from GOES-12 to GOES-13 because of matching solar geometry conditions. The effect of spectral band differences of GOES-12 and -13 visible channels was corrected for by applying spectral adjustments derived from SCIAMACHY. For this correction, SCIAMACHY desert spectra were convolved with the GOES-12 and GOES-13 SRFs to generate pseudo-imager radiances and derive an SBAF. The DCC technique uses the Aqua-MODIS DCC nadir radiance derived over the GOES-13 domain, using GOES-13 images taken near the Aqua satellite overpass times and with the GOES-13 $BT_{11\mu m}$ threshold adjusted to match the Aqua-MODIS $BT_{11\mu m}$. Figure 10 shows the GOES-13 gains derived from all four techniques with excellent agreement.

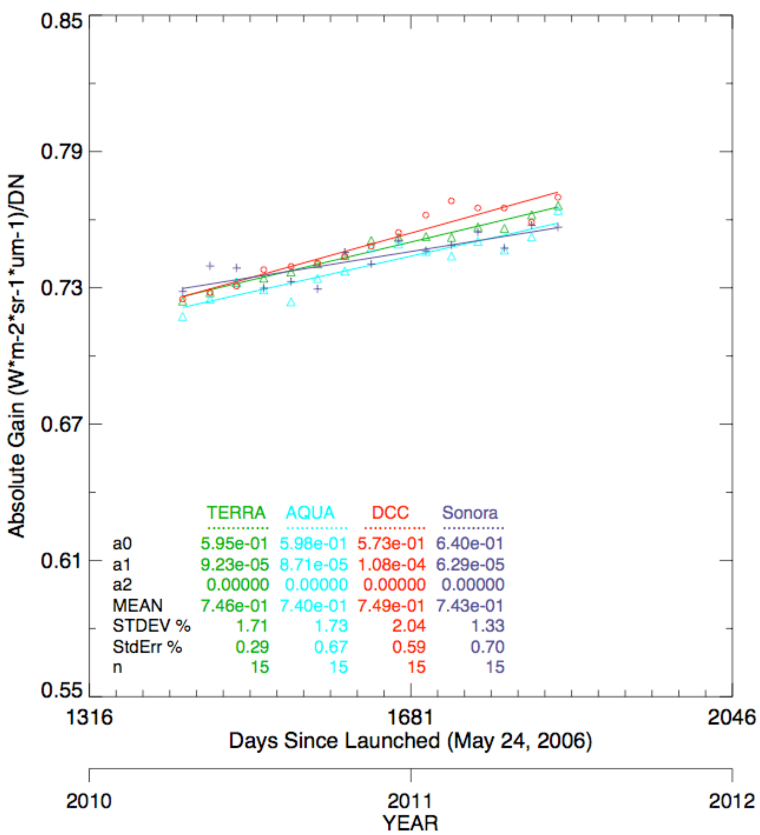

Figure 10: GOES-13 absolute calibration based on 4 independent methods: ray-match with Aqua-MODIS, ray-match with Terra-MODIS, Desert seasonal model absolute calibration, and DCC absolute calibration.

All 4 methods were within 1.4% absolute calibration over the 15 months of analysis. This validates the transfer of the Aqua-MODIS calibration of each of the independent techniques to calibrate GOES-13. It is apparent that these methods suffer from seasonal variations. Therefore, at least a 3-year time period is needed to mitigate the effect of these oscillations and to evaluate the stability over time with each of these methods. Even with these seasonal variations however, the monthly gains are within 2% between methods.

These calibration coefficients were also compared with the NOAA official GOES-13 post-launch operational calibration web site. A least squares fit was applied to the July 2010 to July 2011 monthly gains, where $a_0 = 0.569$ and $a_1 = 9e\text{-}05$, which can be compared with Figure 10. The corresponding NOAA official pre-launch calibration is 0.6118. The NOAA post-launch operational calibration[13] is based on a histogram equalization approach using coincident and collocated, but not co-angled, GOES-13 and MODIS pixel level radiances. The NOAA slope is very similar to the GOES-13/MODIS ray-matching slopes in Figure 10. This is expected, since the NOAA approach most resembles the ray-matching technique presented in this study. However the absolute calibration difference on Jan 1, 2011 between NOAA and CERES ray-match Terra or Aqua-MODIS/GOES-13 is 4.2% or 3.3%, respectively. This is mainly due to the difference in the application of the SBAF correction. Wu and Sun use MODTRAN4 MODIS and GOES-10/12 simulated radiances and report that both GOES-10 and 12 have 4% lower radiances than MODIS and that it is a linear function. The SCIAMACHY based pseudo radiances indicate that the SBAF correction is not linear[2] and for bright targets the GOES-10 and 12 radiance is lower by only ~1% than MODIS. Interestingly, the SRF for GOES-13 is rather different than GOES-12, since the bright target radiance for GOES-13 is greater by 4% then MODIS (see Figure 1c RMAX value). Also the DCC, desert, and ray-match calibration approaches each apply a unique SBAF correction, based on the calibration target spectra shown in Figure 1a. The resultant GOES-13 absolute calibrations are within 1%, based on the Figure 10 15-month gain means, indicating the robustness of the SCIAMACHY based SBAF corrections.

7. CONCLUSIONS

Three independent calibration techniques were presented to transfer the calibration of Aqua-MODIS band 1 to GOES-13. In this study Aqua-MODIS is used as the calibration reference, since it is better characterized and more stable than Terra-MODIS. The ray-matching technique uses bore-sighted radiance pairs to transfer the reference sensor calibration and the technique is dependent on the reference sensor stability. The ray-matching technique was validated using Aqua-MODIS/Terra-MODIS pairs and Terra-MODIS/GOES-13 pairs and compared directly to Aqua-MODIS/GOES-13 pairs. The absolute calibration difference was within 0.8% over the GOES-13 record. Two Sonora Desert invariant target approaches were evaluated. Both Sonora Desert techniques are dependent on the site stability. The seasonal and kernel approaches used GOES-12 calibrated radiances, based on Aqua-MODIS ray-matching, to develop seasonal and BRDF models. These models were then applied to GOES-13. The absolute calibration difference between these approaches was 0.5%, validating the robustness of both methods. The third technique used DCC as invariant earth targets. The Aqua-MODIS calibration transfer using this method depends on identifying DCC targets viewed by both Aqua-MODIS and GOES-13. Aqua-MODIS and GOES-13 probability density functions (PDFs) of normalized visible DCC radiance pixel level radiances were derived monthly. The Aqua-MODIS calibration is transferred by assuming that the normalized DCC radiance is equivalent between GOES-13 and Aqua-MODIS. A generalized GOES-13 DCC approach using the Aqua global DCC radiances with GOES-13 noon DCC radiances and a refined approach that uses DCC targets observed by both Aqua-MODIS and GOES-13, by limiting the domain over the GOES-13 sub-satellite point, using comparable $BT_{11\mu m}$ threshold and coincident time range. It was found that using the PDF mode DCC response was more consistent over the PDF mean DCC response between the DCC approaches. Both DCC approaches had an absolute calibration difference of 0.2%, indicating that DCC target are indeed invariant. The absolute calibration difference between the three techniques was 1.4% during the 15 month record of GOES-13. The excellent consistency of the calibration between methods, validates each of the methods as independent calibration techniques. The SRF difference between GOES-13 and Aqua-MODIS band 1 was corrected using pseudo SCIAMACHY footprint radiances observed over each the calibration targets. Each method had an independent SBAF adjustment. Again the calibration agreement between the methods validates the SBAF adjustment methodology. Based on the CERES calibration strategy the GOES-13 sensor response has degraded by around 5-6 percent in first 15 months of operation but appears linear over time.

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